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Study of the influence of rapidly quenched aluminum alloy on the wear resistance of ultra-high-molecular-weight polyethylene

A.-M.V. Tomina[0000-0001-5354-0674], **D.V. Yakovenko***[0009-0003-1499-9054], **V.F. Bashev**[0000-0002-3177-0935], **S.I. Golovko**[0009-0004-3916-5205]
Dniprovsk State Technical University, Kamyanske, Ukraine
**E-mail: dimyak.pr@gmail.com*

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Abstract

The article considers the influence of 5-30 wt.% dispersed (50-100 µm) AlMnCrVZrCuMgW alloy rapidly quenched from the liquid state on the wear resistance of ultra-high-molecular-weight polyethylene under different operating conditions. In particular, we studied the behaviour of the metal-polymer composite under the action of rigidly fixed abrasive particles and friction conditions without lubrication according to the "disk-pad" scheme. This simulates real operating conditions in tribological joints of mechanisms of modern machinery. The results of experimental studies showed that introducing the rapidly quenched AlMnCrVZrCuMgW alloy into the composition of the polymer material contributes to a significant improvement in its wear resistance in different modes. Thus, the abrasive wear index decreases 1,7 times compared to pure ultra-high-molecular-weight polyethylene. And the intensity of linear wear decreases more than 13 times. The maximum effect was achieved at an alloy content of 20 wt.%. This occurs because of the effective ratio of intermolecular interaction of the components and the uniform distribution of the filler in the polymer volume. The increase in wear resistance is due to the increase in the resistance of the ultra-high-molecular-weight polyethylene surface to mechanical stress. This is confirmed by an increase in the hardness of the material by 1,46 times. Morphological analysis of the friction surfaces revealed a decrease in the number and depth of the ploughing grooves, which is additional confirmation of the effective action of the AlMnCrVZrCuMgW rapidly quenched alloy as a strengthening phase.

Keywords: ultra-high-molecular-weight polyethylene, rapidly quenched alloy, abrasive wear index, linear wear intensity

Introduction

In the constantly complicated operating conditions of mechanisms and equipment of modern machinery, increasing the wear resistance of parts of structural (protection of header bottoms, bearing housings, scrapers) and tribotechnical (sliding bearings, gears) purpose is of particular importance. This directly affects their reliability and durability. This is because traditional materials, particularly metals and alloys, are gradually losing their versatility due to several limitations, including susceptibility to corrosion, large mass, scarcity of raw materials and increasing cost of mechanical processing. This necessitates the search for alternative materials that would meet modern operational requirements and simultaneously be economically feasible. One of the effective solutions to this problem is the creation of polymer composite materials (PCMs) based on thermoplastic polymers filled with effective functional dispersed fillers (FLs). Such materials are characterized by high wear resistance, in particular in conditions of limited or complete absence of lubrication, as well as excellent resistance to X-ray and ultraviolet radiation, corrosion, moisture, and the action of aggressive media (acids, salts, organic solvents and alkalis). In addition, PCMs allow for the implementation of fast technological cycles of forming products without welding or mechanical joining being needed [1,2].

One of the commonly used polymers in the composition of PCMs is ultra-high-molecular-weight polyethylene (UHMWPE). This is due to its high-performance properties such as resistance to dynamic and fatigue loads. The use of functional dispersed FLs, in particular ordinary and oxidized graphite, hexagonal boron nitride [3, 4], graphene oxides, aluminium, zinc and zirconium [5, 6], molybdenum disulfide [7], carbon black [8], allows obtaining PCMs with increased wear resistance, hardness, impact strength, and a low coefficient of friction. Significant interest among dispersed fillers is caused by rapidly quenched (r.q.) alloys based on aluminium. This is explained by the fact that their ultrafine-grained structure, which is formed during rapid cooling, contributes to obtaining fillers with high physical and mechanical properties. Given the above, searching for new PCM compositions based on UHMWPE remains an urgent task in materials science.

The purpose of the work

Taking into account the above, this study focuses on investigating how a powder filler — an alloy composed of AlMnCrVZrCuMgW — affects the tribological performance of polymer composite materials based on UHMWPE, with the objective of enhancing their wear resistance under different frictional conditions.

Objects and methods of research

UHMWPE of Jiujiang Zhongke Xinxing New Material Co., Ltd. [9] was chosen as a matrix for wear-resistant polymer composites. We chose dispersed (40-100 μm) r. q. eight-component AlMnCrVZrCuMgW alloy (Table 1) as the FL when creating new samples of metal-polymer composites (MPCs). This r. q. alloy is characterized by high wear resistance and hardness, thermal stability, and chemical inertness. These properties are due to the high level of microstresses in the crystalline fcc lattice of the aluminium-based substitution solid solution. They arise due to a significant difference in the atomic radii of aluminium and other alloying elements (Table 1). This makes the specified alloy an effective FL for creating MPC with high functional properties.

The production of UHMWPE samples and MPCs with a 5-30 wt.% alloy content was performed by the compression pressing method according to the regime given in [9]. The theoretical density of the AlMnCrVZrCuMgW alloy was calculated by the following formula to obtain samples of the required shape:

$$\rho_{сп} = x_1 \cdot \rho_1 + x_2 \cdot \rho_2 + \cdots + x_n \cdot \rho_n$$

where x_n is a mass percentage of metal in aluminium;

ρ_n is a tabular density (g/cm3) of this metal (Table 1).

Table 1

Composition and properties of the components of the AlMnCrVZrCuMgW alloy

Chemical element	Content, wt.%	Atomic radius, pm	Density, g/cm^3
Al	87,6	142	2,70
Mn	6,0	127	7,21
Cr	2,0	128	7,19
V	0,3	134	6,11
Zr	0,6	160	6,52
Cu	0,4	128	8,96
Mg	2,8	160	1,74
W	0,3	139	19,25

The average density of the alloy was 3.14 g/cm^3. The abrasive wear index for rigidly fixed abrasive particles (at a dispersion of 100 μm) was determined using the HECKERT experimental device at a constant load of 10 N. The study of the tribological properties of UHMWPE and MPCs based on it under friction conditions without lubrication was performed in rotational motion (ν=380 rpm) according to the “disk-pad” scheme in a pair with a steel cylindrical counterbody (steel 45, ø25 mm, hardness 45-48 HRC and surface roughness R_a=0.32 μm) at a constant sliding speed of 1.0 m/s and a load of 1.0 MPa on the SMC-2 friction machine. The hardness of UHMWPE and MPCs on the Rockwell HRR scale (pre- and total load were 98.1 N and 588.4 N, respectively) was determined using the 2074 TPR instrument. Morphological analysis of the friction surfaces of samples from UHMWPE and MPCs was performed using a BIOLAM-M optical microscope. Measurement of the surface roughness of the samples after friction (R_a scale, μm) was done using a 170621 probe profilometer.

Results analysis and discussion

In the course of research, we found that the new compositions of the MPCs are characterized by greater wear resistance compared to the UHMWPE (see Table 2). It is 1.7 times higher in the case of abrasive wear on rigidly fixed particles, and 13.2 times greater in the case of friction without lubrication according to the "disk-pad" scheme. The increase in wear resistance is because of the rise in the resistance of the MPCs to mechanical loads [9], which is confirmed by the increase in the hardness of the material and the decrease in the roughness of its surface after testing by 1.46 times [9].

Table 2

Operational properties of UHMWPE and MPCs based on it

FL content, wt.%	Abrasion index*, Vi, mm3/m	Intensity of linear wear **, $I_h \cdot 10^{-7}$	Hardness HRR, Hardness units***	Roughness*** Ra, µm	
				under the influence of rigidly fixed abrasive particles	under friction conditions without lubrication
0	1,48	15,8	32	2,78	2,14
5	1,40	10,6	35	2,53	2,02
10	1,31	6,2	39	2,35	1,89
15	1,22	2,7	43	2,13	1,75
20	0,86	1,2	47	1,92	1,63
25	1,06	3,1	45	2,16	1,77
30	1,14	5,5	40	2,43	1,82

*average of three study cycles
**average of three experiments
***average of 12 measurements

It should be noted that with an increase in the number of test cycles (Fig. 1), a decrease in the abrasive wear index is observed for both UHMWPE and MPCs based on it. This is explained by the gradual filling of the micro-irregularities of the abrasive surface with finely dispersed wear products, which leads to the effect of the so-called "greasing" of the surface.

A comparison of the morphology of the friction surfaces (Fig. 2) under different operating conditions showed that the MPCs have a more homogeneous and less damaged surface compared to pure UHMWPE. In particular, we observe a decrease in the number of deep grooves and microcracks on the friction surface of the composite with an effective FL content of 20 wt.%, which indicates higher resistance to mechanical wear. There are signs of intense plastic deformation and destruction of the structure because of friction on the surface of pure UHMWPE under friction conditions without lubrication, in contrast to the MPCs [10].

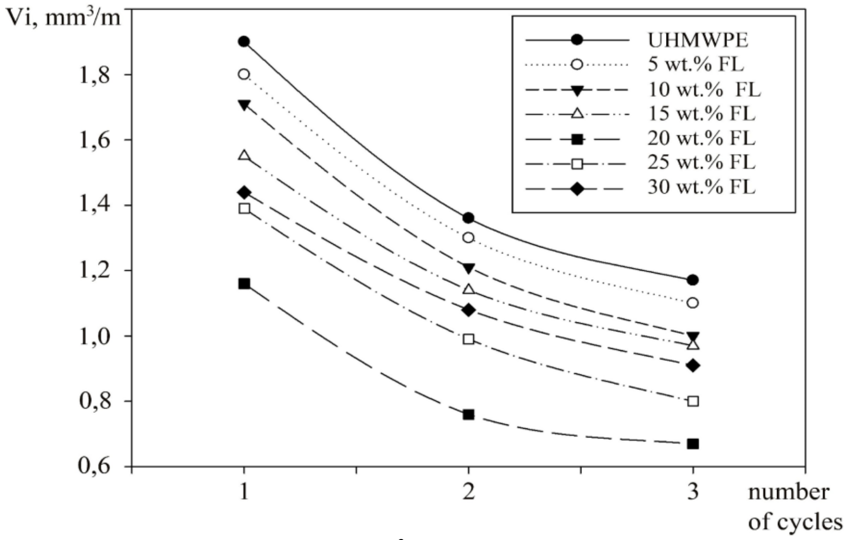
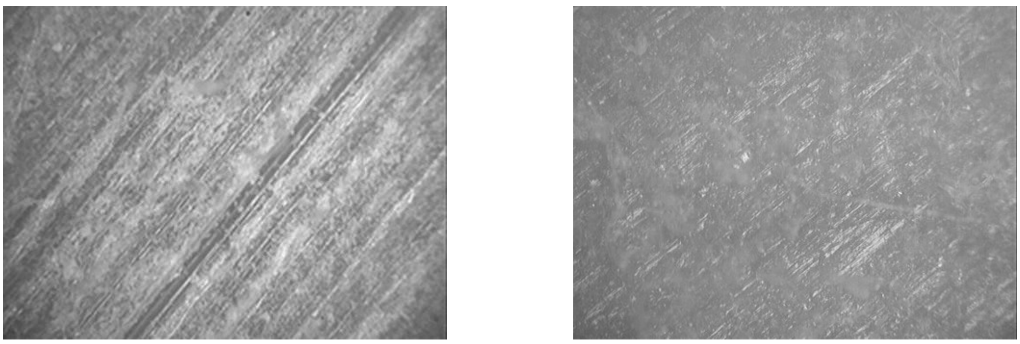
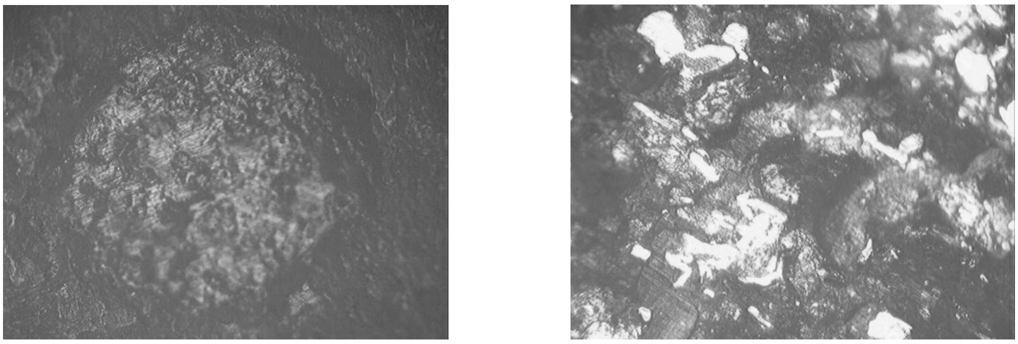


Fig. 1. Dependence of the abrasive wear index (Vi, mm³/m) of ultra-high-molecular-weight polyethylene and MPCs based on it on the number of study cycles



a



b

Fig.2. Friction surfaces (×200) of pure UHMWPE (a) and MPC (b) based on it, containing 20 wt.% FL in different operating modes: under the action of rigidly fixed abrasive particles (1) and under friction conditions without lubrication according to the "disk – pad" scheme

It is worth noting that there is a decrease in the wear of the MPCs in the filling range of 5-20 wt.%. This is due to the uniform distribution of FL in the UHMWPE. However, with a further increase in the alloy content to 25-30 wt.%, there is a reverse trend, and the wear resistance decreases. This may occur because aggregates of filler particles form, the homogeneity of the MCP structure is disrupted, and the stress concentrators appear due to the above [11]. As for the friction coefficient, its average 15% increase was recorded, which is typical for composites with a metal FL.

Conclusions

It was found that the introduction of 5-30 wt.% AlMnCrVZrCuMgW alloy contributed to an increase in the wear resistance of the UHMWPE during abrasive wear on rigidly fixed particles by 1.7 times, and by 13.2 times under friction conditions without lubrication according to the "disk-pad" scheme, reaching minimum values at 20 wt.% FL. We recommend using a composite with an effective FL content of 20 wt.% for the manufacture of parts of structural (protection of the bottoms of headers, bearing housings, scrapers) and tribotechnical (sliding bearings, gears) purpose of elements of mechanisms and equipment of modern machinery.

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Томіна А-М.В., Яковенко Д.В., Башев В.Ф., Головко С.І. Дослідження впливу швидкозагартованого алюмінієвого сплаву на зносостійкість надвисокомолекулярного поліетилену

У статті розглянуто вплив дисперсного (50-100 мкм) швидкозагартованого з рідини сплаву AlMnCrVZrCuMgW у кількості 5-30 мас.% на зносостійкість надвисокомолекулярного поліетилену за різних режимів експлуатації. Зокрема, досліджено поведінку металополімерного композиту під дією жорстко закріплених часток абразиву, а також в умовах тертя без змащення за схемою «диск – колодка», що моделює реальні умови експлуатації у трибологічних з'єднаннях машин і механізмів сучасної техніки. Результати експериментальних досліджень показали, що введення швидкозагартованого сплаву AlMnCrVZrCuMgW до складу полімерного матеріалу сприяє істотному покращенню його зносостійкості у різних режимах. Так, показник абразивного стирання зменшується у 1,7 рази порівняно з чистим надвисокомолекулярним поліетиленом, а інтенсивність лінійного зношування – більш ніж у 13 разів. Максимального ефекту досягнуто при вмісті сплаву 20 мас.%, що зумовлено ефективним співвідношенням міжмолекулярної взаємодії компонентів і рівномірним розподілом наповнювача в об'ємі полімеру. Підвищення зносостійкості обумовлено зростанням опору поверхні надвисокомолекулярного поліетилену до механічного навантаження, що підтверджується збільшенням твердості матеріалу у 1,46 рази. Морфологічний аналіз поверхонь тертя виявив зменшення кількості та глибини борозен проорювання, що додатково є підтвердженням ефективної дії швидкозагартованого сплаву AlMnCrVZrCuMgW як зміцнювальної фази. Металополімерний композит із ефективним вмістом наповнювача 20 мас.% може бути рекомендований для виготовлення деталей конструкційного (захист днищ жаток, корпуси підшипників, чистики) та триботехнічного (підшипники ковзання, шестерні) призначення елементів машин і механізмів сучасної техніки. Використання таких матеріалів забезпечить підвищення довговічності на надійності трибологічних з'єднань машин і механізмів техніки, що зазнають інтенсивного зношування під час експлуатації.

Ключові слова: надвисокомолекулярний поліетилен, швидкозагартований сплав, показник абразивного стирання, інтенсивність лінійного зношування.